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Improving the Rod-Penetration Algorithm for Tomorrow's Armors

by Steven B. Segletes, Rick Grote, and John Polesne

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Abstract

The performance of the respected Frank-Zook penetration algorithm (Zook, J. A., Frank, K., and Silsby, G. F., "Terminal Ballistics Test and Analysis Guidelines for the Penetration Mechanics Branch," BRL-MR-3960, January 1992) is examined in light of an anticipated class of target technologies involving laminated targets whose layers are thin relative to the projectile diameter. This class of target designs encompasses multifunctional integral armors and, in the limiting case, armors incorporating functionally-graded materials. Such armor classes represent potential candidates for the Army's Future Combat System. The ability to effectively model the ballistic response of advanced armors is paramount to accurately assessing system lethality and vulnerability for future weapon systems and platforms.

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IMPROVING THE ROD-PENETRATION ALGORITHM FOR TOMORROW'S ARMORS

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ABSTRACT

The performance of the respected Frank-Zook penetration algorithm (Zook *et al.*, 1992) is examined in light of an anticipated class of target technologies involving laminated targets whose layers are thin relative to the projectile diameter. This class of target designs encompasses multifunctional integral armors and, in the limiting case, armors incorporating functionally-graded materials. Such armor classes represent potential candidates for the Army's Future Combat System. The ability to effectively model the ballistic response of advanced armors is paramount to accurately assessing system lethality and vulnerability for future weapon systems and platforms.

1. MOTIVATION

The Survivability/Lethality Analysis Directorate (SLAD) and the Weapons and Materials Research Directorate (WMRD) of the Army Research Laboratory (ARL) are jointly working in the area of Target Interaction Lethality/Vulnerability (TILV) – Ballistic Damage of Advanced Material and Armor Systems. SLAD is upgrading their MUVES S2 suite of vulnerability/lethality models (Hanes *et al.*, 1988) as part of the TILV program. Vulnerability/lethality models are being constantly challenged by new, sophisticated and complicated armor technologies. Although there can be tremendous variations in these new technological advances, they can be generalized under the following categories: spaced and layered solutions, reactive and passive appliqués, ceramic solutions, impact-energy absorption techniques, advanced metals and matrix geometries, functionally graded materials (FGMs), electromagnetic techniques, and polymer solutions (transparent armors). These new armor design technologies are surfacing as potential candidates for both foreign and U.S. ground/air combat systems. The U.S. Army's Future Combat System may include many of these armor classes.

To understand the implications of these new ballistic-protection technologies before they become fielded on future systems, this collaborative effort has been established to develop a physically-based penetration model that is suitable for implementation into the MUVES S2 suite of models. A "building block" approach has been adopted wherein the currently utilized penetration equations are first examined and refined to better estimate the ballistic performance of laminated spaced armor solutions versus kinetic energy projectiles, with an eye towards eventually developing penetration equations to accurately estimate the ballistic response of FGMs.

Traditional penetration methodologies, like those of Tate (1967) and Alekseevskii (1966), were developed for rods penetrating idealized semi-infinite target blocks. As such, target resistance variations along the shotline were not an issue. Later analyses (Wright and Frank, 1988; Tate, 1986; Walker and Anderson, 1995) showed that the property of target resistance represents an integral of stresses throughout the plastic zone in the target, ahead of the rod/target interface. In the course of penetration, when this plastic zone crosses the interface between two adjacent target plies, one may infer that the local target properties should be properly composed of material properties from both of the entrained plies. In this manner, the transition of "effective" material properties penetrating from one target ply into the next should be continuous, rather than discrete.

The Frank-Zook (FZ) penetration algorithm (Zook *et al.*, 1992), used widely within the ARL for both terminal ballistic evaluation and vulnerability assessment, considers this interply transition process. However, since it was developed when long rods and relatively thick target elements represented the prevalent engagement scenario, the FZ algorithm computes this transition effect a single target element at a time (*i.e.*, it only senses one target element in advance).

The FZ algorithm can accurately sense and respond to the situation where, for example, the penetration channel proceeds from a weak target element into a strong target element. The effective resistance offered by the target would gradually and smoothly transition from the weak value, just reaching the strong value of resistance as the penetrator/target interface reaches the strong target element. If a rod of diameter D is penetrating target element i, the influence of target element i+1 upon the effective target resistance $\overline{H}$ is evaluated by the FZ model as

$$\overline{H} = H_i + \left(H_{i+1} - H_i\right) e^{-2T_{res}/3D} \quad , \tag{1}$$

where the H_i are the target-element component resistances, and T_{res} is the residual, normal thickness of target element i yet to be penetrated. In the absence of this modeling enhancement, the transition in target resistance would be unrealistically abrupt.

However, implementing this realistic enhancement within the FZ algorithm is accomplished only a single interface at a time (*i.e.*, target elements i+2, *etc.* do not affect the effective resistance). Thus, if the finite target volume contributing to the target resistance realistically entrained several target/target interfaces, the FZ algorithm would only account for the one closest to the penetrator/target interface. Such a situation can realistically arise in several situations. One is where there exists a target composed of elements that are thin compared to the penetrator diameter, possibly as in the case of targets designed for small- and medium-caliber threats. In this case, the plasticity zone will entrain not two, but a larger number of target element layers simultaneously (Fig. 1). For such targets, the FZ algorithm will be ill-suited to model the transition of "effective" target resistance and density along the shotline. Though the problem can be quite severe when the target-layer thickness is a fraction of the projectile diameter, the effect is still evident to a much lesser extent, even as the target-element thickness is increased to several projectile diameters.

Another example in which several target/target interfaces could be entrained in the zone of target material contributing to target resistance is when a target element is barely clipped by the penetrator shotline. This latter situation can arise even if the individual target elements are otherwise thick. And since, from the point of view of a statistical vulnerability computation, the process of selecting and calculating penetrator shotline geometries is fully automated, the vulnerability analyst has little or no control in preventing very thin target elements from arising along a given shotline geometry, even for large-caliber targets.

2. DISCUSSION

A remedy to these types of problems is offered and accomplished by a novel adaptation of elements from a model by Walker and Anderson (1995) into the FZ framework. In so doing, the target's material properties and nonsteady-kinematic properties are dynamically composed via an integration through the plastic zone in the target, ahead of the rod/target interface. Though the Walker-Anderson model does not even address the issue of multilayer targets, the assumed flow field kinematics of their model provide enough information to isolate and dynamically calculate an integrated contribution from each layer in a given laminate target towards the aggregated or "effective" target properties.

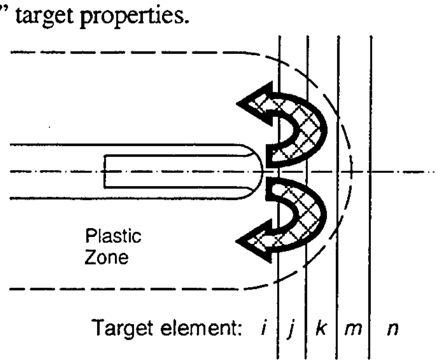


Fig. 1. Plastically entrained elements contribute to "effective" target properties, e.g., resistance $H = H(i, j, k, m)$.

This integration is accomplished by using the extended Bernoulli equation (Segletes and Walters, 1999) to yield the relation that governs the rod/target interaction. The equation includes aggregated terms summed from all of the layers of target material entrained in the plastic zone:

$$\left(k_P - \frac{1}{2}\cdot\frac{\dot{s}}{L}\right)\rho_P (V-U)^2 + Y - \frac{\rho_P s}{2}(\dot{V}+\dot{U}) = k_T\bar{\rho}U^2 + \bar{H} + X_U\frac{\dot{U}}{U} + X_\alpha\frac{\dot{\alpha}}{\alpha} + X_R\frac{\dot{R}}{R} \quad , \qquad (2)$$

where k_P, ρ_P, Y, V, and s are the shape factor, density, strength/resistance, velocity, and plastic-zone extent in the rod of length L and diameter D, while k_T, $\bar{\rho}$, $\bar{H}$, U and α are the corresponding values for the target interface. The X terms are nonsteady-influence terms defined below. Namely, for a plastic zone of thickness $(\alpha - 1)$ times the crater radius R, spanning across target elements $i = m$ to n, of density ρ_{Ti}, where the $(i-1) \rightarrow i$ intra-target interface is positioned at $z = (\beta_i - 1)R$ with respect to the rod/target interface (with $\beta_m = 1$, $\beta_{n+1} = \alpha$), the following generalized expressions for the target parameters are obtained:

$$\bar{\rho} = \sum_{i=m}^{n} \frac{\alpha^4}{(\alpha^2-1)^2}\left[\frac{(2\beta_i^2-1)}{\beta_i^4} - \frac{(2\beta_{i+1}^2-1)}{\beta_{i+1}^4}\right]\rho_{Ti} \quad , \qquad (3)$$

$$\bar{H} = \sum_{i=m}^{n} \frac{\ln(\beta_{i+1}/\beta_i)}{\ln(\alpha)} H_i \quad , \qquad (4)$$

$$X_U = UR\sum_{i=m}^{n} \frac{\rho_{Ti}}{(\alpha^2-1)}\left[\frac{(\beta_i^2+\alpha^2)}{\beta_i} - \frac{(\beta_{i+1}^2+\alpha^2)}{\beta_{i+1}}\right] \quad , \qquad (5)$$

$$X_\alpha = UR\sum_{i=m}^{n} \frac{2\rho_{Ti}\alpha^2}{(\alpha^2-1)^2}\left[\frac{(\beta_{i+1}^2+1)}{\beta_{i+1}} - \frac{(\beta_i^2+1)}{\beta_i}\right] \text{, and} \qquad (6)$$

$$X_R = UR\sum_{i=m}^{n} \frac{\rho_{Ti}\alpha^2}{(\alpha^2-1)}\left[\frac{(2\beta_i-1)}{\beta_i^2} - \frac{(2\beta_{i+1}-1)}{\beta_{i+1}^2}\right] \quad . \qquad (7)$$

These results reduce to those of Walker and Anderson (1995) for the case of monolithic targets, wherein $m = n = 1$, and the limits on β correspond to the extent of the plastic zone as $\beta_1 = 1$, and $\beta_2 = \alpha$.

3. RESULTS

A test series was conducted by personnel at ARL's Experimental Facility 110, using the 14.5 mm B32 armor-piercing projectile, weighing 63.5 g and consisting of a 53 mm, 41 g hardened-steel (Rc 65) core surrounded by a brass jacket (Fig. 2). The gun-breech powder loading was altered to systematically vary the projectile velocity.

The projectile was modeled as a 63.5 g homogeneous steel slug, 66.5mm long × 12.45mm diameter, equaling the overall length and mass of the B32 projectile. Because the sharpened B32 core penetrates as a rigid body, the shape factor, k_T, of the target flow was set to 0.15 rather than 0.5, reflecting the reduced momentum transfer imparted to a sharpened body as compared to the stagnation flow of bluntbody penetration. This revised k_T value is based on the fact that the force required to turn an inviscid flow through an angle of θ is proportional to $(1 - \cos\theta)$. This suggests that k_T take on the value $1/2\ (1 - \cos\delta)$, where δ is the half-angle of the rigid-projectile nose, approximately 45° for the tip of the B32 core. It is important to note that without accounting for the influence of both the brass-jacket mass and the pointed aspect of the rigid core, the calibration tests of B32 penetration into "semi-infinite" 5083 aluminum underestimated the penetration, as shown in Fig. 3.

Into semi-infinite and finite-plate targets, the FZ and revised models both perform well, as anticipated and shown in Fig. 4. The material modeling parameters for all calculations are given in Table 1. Values for target resistance were selected to fit the data, but are compatible with various analytical estimation techniques. Plastic-zone extent values will be subsequently discussed. The slight discrepancy between models was caused by introducing the integrated (*i.e.*, "effective") and nonsteady terms of equation (2) in the revised modeling approach.

However, to appreciate the distinction between the original and revised methodology, consider the 23 mm plate of 5083 aluminum that composed the target of Fig. 4b, and augment the target by adding a 0.8 mm mild-steel backing plate to the rear of the aluminum plate. Fig. 5 presents the data as well as modeling predictions, including those for the original configuration without the steel backing. The addition of this thin plate should have a minimal effect on the ballistic resistance of the target, which is indeed reflected in the data. And while the revised modeling

Table 1. Material Modeling Parameters*

Projectile Material	ρ_P (kg/m³)	Y (GPa)	
Steel (Rc65)	7850	4.46	
Target Material	ρ_T (kg/m³)	H (GPa)	Plastic Zone Extent *PZE/D*
5083 Al. (BHN 103)	2700	1.92	5.1
Mild Steel (BHN 93)	7850	2.09	3.5
HHA (BHN 500)	7850	6.15	3.5
Acrylic	1190	0.62	3.5

*Target rear surfaces modeled with 0.5GPa spall strength

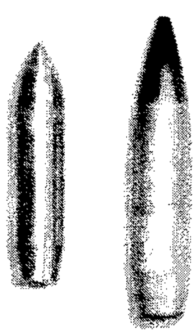


Fig. 2. The B32 armor-piercing core and projectile.

corroborates this minimal influence, the original model improperly accentuates the effect. However, it is not the resistance of steel backing that in and of itself produces this effect in the original model. Rather, the error is introduced while penetrating the aluminum plate, since the rod is at that moment unaware that the target rear surface exists. As such, it is the failure to perceive incipient breakout (and the associated diminution of resistance) while penetrating the aluminum that results in the underestimation of residual velocity, V_r, by the original model.

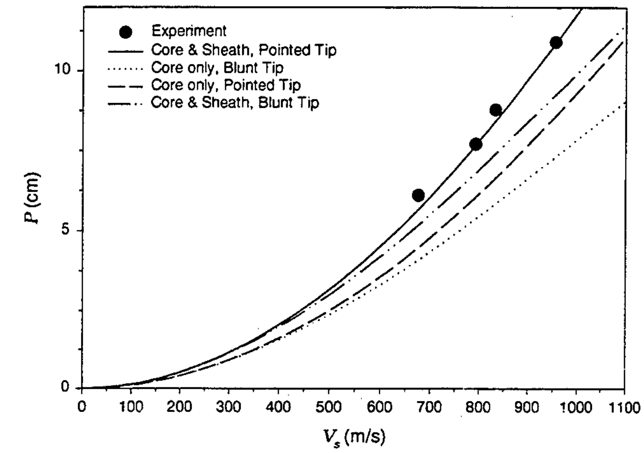


Fig. 3. Penetration of B32 into 5083 aluminum using various modeling assumptions.

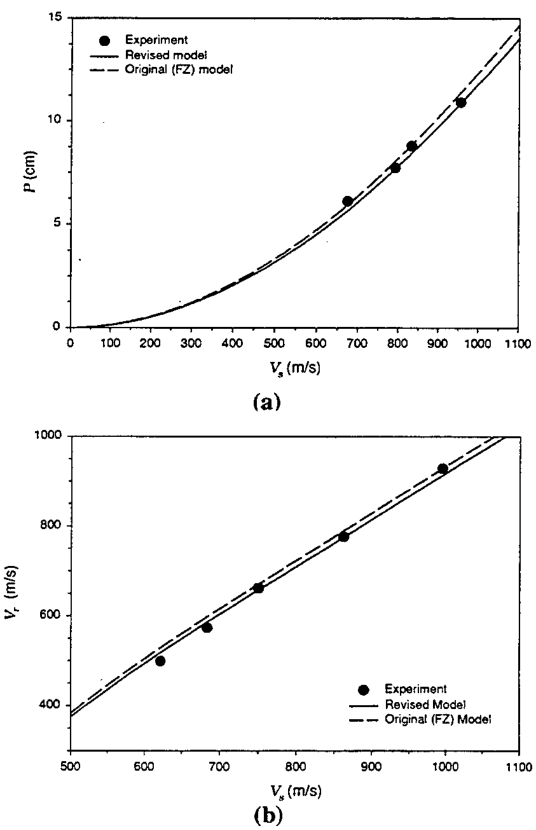


Fig. 4. Comparison of FZ model and revised model for B32 against (a) semi-infinite 5083 aluminum, and (b) 23 mm plate of 5083 aluminum at 0° obliquity.

As a second example, consider the same 23 mm target of 5083 aluminum, this time backed by a 9.6 mm high-hard armor (HHA) plate. Even though the HHA element is not nearly so thin as the mild-steel backing of the previous example, it is still thin enough, relative to the 12.45 mm projectile core, for the original model to suffer the identical problem for the same reason, as shown in Fig. 6. For the original model to better match the data, the HHA target resistance would have to be lowered nearly 40% to an artificially low value of 3.75 GPa.

To remove any lingering doubt that the root of the original model's problem arises from its treatment of subsequent target elements only one at a time, consider the aluminum/HHA target under discussion with a 2.8 mm acrylic interply between the aluminum and HHA. While it may be surmised that the interply's contribution to the target's ballistic resistance should be minimal, that influence should nonetheless be a trend of slight strengthening. Thus, the residual-velocity curves of Fig. 7 depict both the inconsistency that can occur when the model can only sense one advance target-element at a time, as well

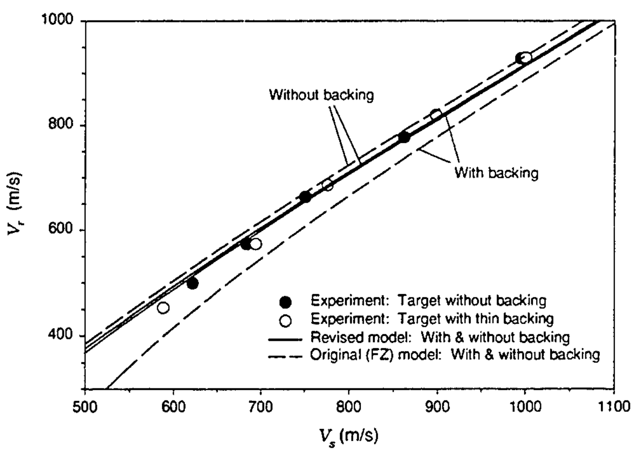


Fig. 5. Comparison of FZ model and revised model for B32 against 23 mm plate of 5083 aluminum with and without 0.8 mm mild-steel backplate.

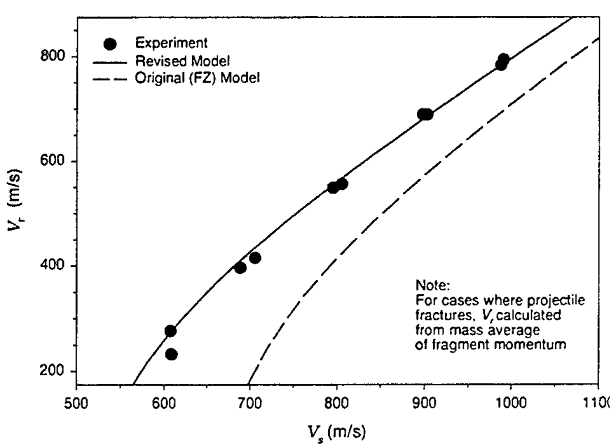


Fig. 6. Comparison of original and revised models for B32 vs. target consisting of 23 mm 5083 aluminum plus 9.6 mm HHA.

as the correction offered by the revised modeling. Contrary to both expectation and data trend, adding the acrylic interply significantly weakens the overall target resistance, according to the original methodology. The cause for this inconsistent behavior may be understood from Fig. 8, which portrays the target resistance as a function of location through the target.

3.1 Analysis of Model Parameter Influence

In particular, Fig. 8 depicts how the original model perceives these two target configurations quite differently. For the baseline case without the interply (Fig. 8a), the FZ algorithm properly senses the influence of the strong HHA plate while penetrating the 5083 aluminum, but fails to detect the rear surface of the target prior to actually entering the HHA element. Thus, the resistance undergoes a large and instantaneous correction upon entering the HHA plate, since the target free surface then becomes recognized. Because of the overestimated resistance while penetrating the aluminum, the original algorithm underpredicts the residual velocity (V_r) exiting the baseline target. Once in the HHA plate, only one interface (*i.e.*, the rear surface) is entrained in the target's plastic zone. Consequently, the two models exhibit nearly identical behavior at this point; the small differences are attributable to the difference between the FZ formulation for resistance given by eqn (1) and the revised formulation given by eqn (4).

For the test case containing the acrylic interply (Fig. 8b), the influence of the hard HHA plate is not sensed by the FZ algorithm while penetrating the 5083 element until the acrylic is actually reached. Rather, the 5083 plate senses only the weak acrylic interply. As such, the original algorithm underestimates the target resistance in the aluminum and overpredicts the residual velocity exiting the test-case target.

In contrast, the revised algorithm, by simultaneously accounting for all the relevant target elements and free

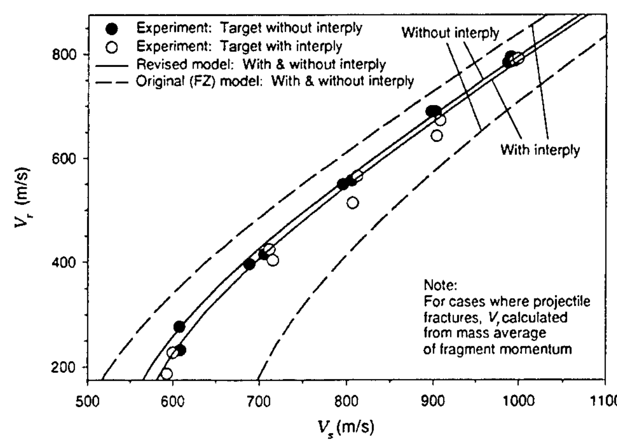
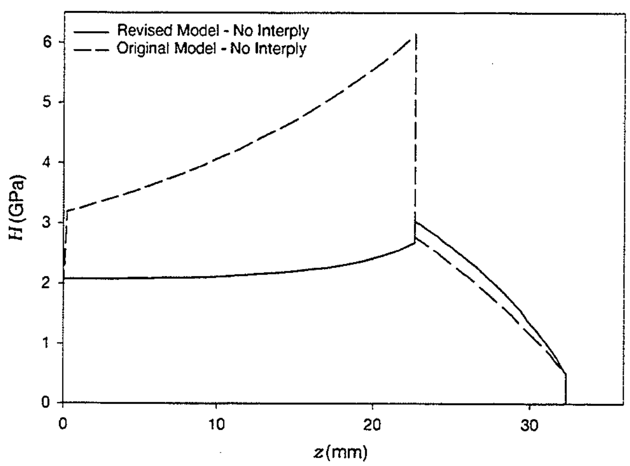


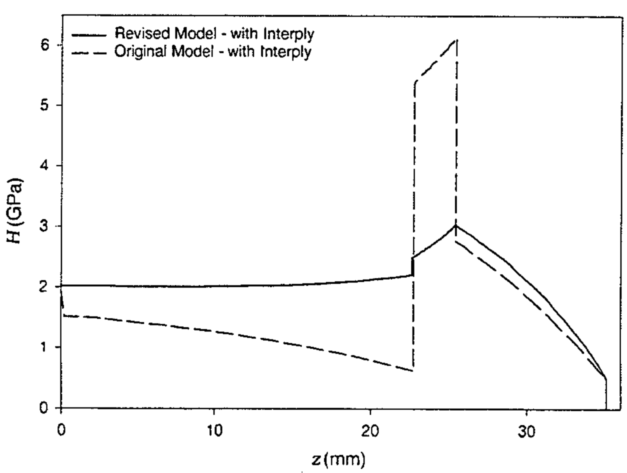
Fig. 7. Effect of 2.8 mm interply layer of acrylic on original and revised models for B32 vs. target consisting of a 23 mm 5083 aluminum plus 9.6 mm HHA baseline.

surfaces in proportion to their actual influence, properly captures both the magnitude and sense of the ballistic trend. While the original formulation can experience large instantaneous jumps in target resistance [recall that one purpose of eqn (1) was to help avoid this occurance], even the revised formulation seen in Fig. 8 experiences a small instantaneous jump of around 0.35 GPa at the rear surface of the 5083 target element. The source of this jump is the difference in plastic-zone extent modeled for the aluminum, compared with that for the other target materials.

Before discussing the influence of the plastic-zone-extent parameter on results of the revised model, the magnitude of this target-resistance jump represents the error introduced by assuming that the flow field in the plastic zone obeys the spatially hemispherical function selected by Walker and Anderson (1995), even as that flow field extends across material interfaces. The use of this flow-field assumption across material interfaces is a valid criticism of the revised formulation, reflecting the fact that the actual plastic zone shape ahead of the rod/target interface will not, in reality, remain hemispherical across an interface of dissimilar materials. However, despite this criticism, the assumption is nonetheless a significant improvement over the original formulation in this regard, as reflected in Fig. 8. A future improvement to the revised model can be achieved by transitioning the plastic-zone extent gradually, as an interface is approached, rather than abruptly, as is currently done. With such an improvement, the target resistance would always remain continuous with position.



(a)



(b)

Fig. 8. Target resistance vs. location for target consisting of 23 mm 5083 aluminum plus 9.6mm HHA, (a) without interply, (b) with 2.8 mm acrylic acrylic interply.

As listed in Table 1, the plastic-zone extent (*PZE*) in the 5083 aluminum was taken as 5.1 projectile diameters, compared with a value of 3.5 for the other target materials. While this alteration was done to improve the fit to data, an analytical method for estimating this parameter from material properties is planned for future work. This alteration to the aluminum's plastic-zone extent provides an opportunity to study this parameter's effect on the revised model. The influence of an alteration in aluminum's *PZE*, from a value of 5.1 to 3.5 on the revised-model predictions, is shown in Table 2 for data from various figures. And while the impact on the model predictions of Fig. 7 may seem large, much of that is attributable directly to the fact that the low-velocity data is very close to the ballistic limit, where small model changes of any type can have a large-percentage influence on the residual velocity. For the data in Fig. 7, the influence of the cited change in *PZE* drops to 7% for striking speeds above 700 m/s, and to under 2% by 1000 m/s striking speed. It appears that model results, at least in the cases studied to date, are not overly sensitive to the selection of this parameter.

4. CONCLUSIONS

When investigating the ability of the current FZ penetration algorithm to predict the ballistic performance of targets comprising thin (or functionally-graded) elements, a deficiency was noted arising from the algorithm's ability to examine the influence of only one leading target element at a time. A remedy has been offered that incorporates elements of a model by Walker and Anderson (1995) into the existing FZ framework. Both models were compared against data for the 14.5 mm B32 penetrator against several target configurations designed to probe the perceived algorithm deficiency. The revised model compares well to data, for several different test cases, offering notable improvement over the original methodology for the cases

Table 2. Influence of Plastic-Zone-Extent Variation

On What	Fig.	Influence of PZE variation from 5.1 to 3.5 $\times D$
Penetration	3	< 0.5%.
Residual Velocity	5	< 2%
Residual Velocity	7	~ 30% at V_s = 580m/s
Residual Velocity	7	~ 7% at V_s = 700m/s
Residual Velocity	7	< 2% at V_s = 1000m/s

studied. These modeling remedies and enhancements are being considered for incorporation into the Army Research Laboratory's MUVES code, as part of ARL's vulnerability/lethality calculation methodology.

ACKNOWLEDGMENTS

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The performance of the respected Frank-Zook penetration algorithm (Zook, J. A., Frank, K., and Silsby, G. F., "Terminal Ballistics Test and Analysis Guidelines for the Penetration Mechanics Branch," BRL-MR-3960, January 1992) is examined in light of an anticipated class of target technologies involving laminated targets whose layers are thin relative to the projectile diameter. This class of target designs encompasses multifunctional integral armors and, in the limiting case, armors incorporating functionally-graded materials. Such armor classes represent potential candidates for the Army's Future Combat System. The ability to effectively model the ballistic response of advanced armors is paramount to accurately assessing system lethality and vulnerability for future weapon systems and platforms.

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